Asymptotic light field in the presence of a bubble-layer

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Abstract: We report that the submerged microbubbles are an efficient source of diffuse radiance and may contribute to a rapid transition to the diffuse asymptotic regime. In this asymptotic regime an average cosine is easily predictable and measurable.

OCIS codes: (010.4450) Ocean optics; (290.4210) Multiple Scattering

References and links

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1 Introduction

The vertical structure of light in the sea is important in marine bio-optics. Sunlight is the energy source for the biological food chain, and the amount and spectrum of solar energy available at a given depth must be known if accurate productivity calculations are to be made. The vertical structure of the diffuse attenuation coefficient in the near surface regime is important in understanding optical remote sensing. The behavior of the light field in the sea is described by the equation of radiative transfer, which relates the light field to the inherent optical properties of water and its constituents [1]. Once this equation is solved certain moments of the light field can be derived and compared with measurements. Of particular interest is the average cosine of irradiance at depth z which is defined by $\bar{\mu}(z) = E(z)/E_0(z)$, where $E_0(z)$ is the scalar irradiance and $E(z)$ is the net (vector) irradiance, both with units Wm^{-2}. The downwelling average cosine is $\bar{\mu}_d(z) = E_d/E_0$, where E_d is the downwelling irradiance. The average cosine, which can vary between -1 and 1, gives directional information about the radiance distribution. The average cosine is also related to the diffuse attenuation coefficient $K(z) = -1/E(z)dE(z)/dz$. Integration of the radiative transfer equation over all directions leads to $dE(z)/dz = -a(z)E_0(z)$ so that $\bar{\mu}(z) = a(z)/K(z)$, which is known as Gershun's equation. We can now measure $a(z)$ and $K(z)$ routinely, so that it is possible to verify predictions of the vertical distribution of $\bar{\mu}$ on the basis of observations. A number of models of the vertical structure of the average cosine of the light field have been presented [1-4] but they have all been limited to homogeneous media with a flat surface. On the other hand, using the data from the Gulf of California and the East Coast shelf one of us (JRVZ, unpublished) concluded that the average cosine models do not fit the determination of $\bar{\mu}(z)$ from $K(z)$ and $a(z)$. It is speculated that this departure from theory is due to vertical inhomogeneities in the inherent optical properties (IOPs) and the possibility that the light field in the surface layer of the ocean may be more diffuse than theoretical models assume. This diffuse light field may be due to haze and clouds in the atmosphere, relatively low solar zenith angles, surface waves, and microbubbles in the surface layer. A combination of these factors contributes to the light field being quite diffuse throughout the water column. In this study we demonstrate the capacity of air bubbles to be an efficient scatterer.

2 Results

There is limited knowledge [5-7] about the radiative transfer properties of bubble clouds, their inherent optical properties, and their global climatology. Recently, we reported [8] on the influence of submerged bubble clouds within the water on the remote sensing reflectance. Individual bubble clouds persist for several minutes and are generated by breaking waves. There is evidence that at high wind speeds, separate bubble clouds near the surface coalesce, producing a stratus layer [9,10]. The majority of bubbles injected into the surface layers of natural waters are unstable, either dissolving due to enhanced surface tension and hydrostatic pressures or rising to the air-water interface where they break [11]. However, bubbles with long residence times, i.e. stable microbubbles have been observed [12-14]. One of the stabilization mechanisms [15,11] assumes that the surfactant material is a natural degradation product of chlorophyll, present in photosynthesizing algae.

We consider three simple situations: (1) “infinitely” deep homogeneous ocean composed of CDOM, water, and particulates; (2) “infinitely” deep homogeneous ocean composed of the same CDOM, water, and particulates but also with bubbles; (3) two meter layer of bubbles and

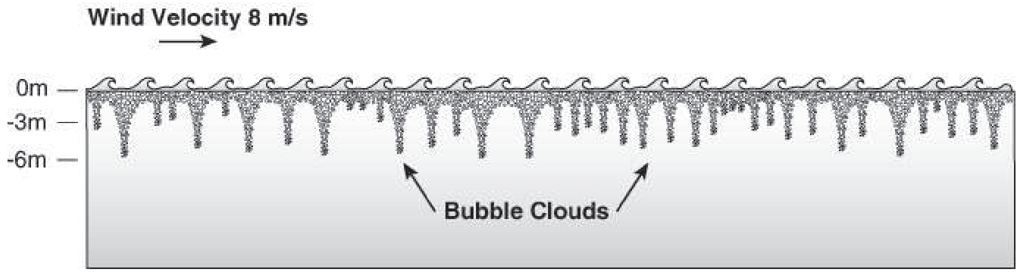

Fig. 1. Bubble-stratus layer generated by breaking waves. Bubble population is continually replenished by wave activity (breaking waves at the surface) leading eventually to semi-homogeneous layer.

"background" CDOM, water, and particulates. In Fig. 1 the two-layer case is presented. (based on [10]).

The background water, CDOM, and particulates are characterized by absorption and scattering coefficients $a = 0.1801\mathrm{m}^{-1}$ and $b = 1.2525\mathrm{m}^{-1}$ (thus we include water a and b). It corresponds to a chlorophyll concentration of $10\mathrm{mgm}^{-3}$ at a wavelength $\lambda = 550\mathrm{nm}$. The particulate phase function is that of Petzold for turbid water [7]. The phase function for bubbles was calculated by averaging from size parameter $x = 10 - 350$, where $x = 2\pi r/\lambda$, r is radius. The size distribution follows a r^{-4} law. A phase function was derived using the exact method for spheres and we assume a refractive index $n = 3/4$. The scattering coefficient for bubbles is assumed to be $b_{\mathrm{bubble}} = 0.6181\mathrm{m}^{-1}$. In our recent paper [8] we discuss in detail the climatology of bubble layer depth, vertical distribution, and dependence of depth on the wind speed. Assumptions made here are typical for $10\mathrm{m/s}$ winds in bubble-stratus regime. The radiative transfer calculations were performed using the Monte-Carlo technique [16]. The main results of this note are presented in Figs. 2-3. Fig. 2 shows the average cosine for the downwelling radiation for the three cases discussed above. In this figure "circles" are for the two-layer system. At first there a is rapid decrease in the value of the average cosine as initially collimated photons are efficiently scattered. After exiting the "bubble" layer the light is already diffuse and only a small adjustment is needed to attain an asymptotic regime for the "no bubbles" situation. This double-exponential transition mechanism seems to be particularly efficient in establishing the near-surface diffuse light field. Clearly, the depth of the bubble layer and the inherent optical properties will further determine this efficiency. Fig 3 shows $\bar{\mu}(z)$, which contains contribution from the upwelling radiation as well. The upwelling radiance field adjusts gradually when photons interact with the "bubble" layer. There is preferential loss of photons traveling in the horizontal direction. This leads to more collimated light and increased average cosine close to the surface. In reference [8] we discuss in more detail the climatology of bubble clouds, which strongly depends on wind speed. The importance of bubbles on an asymptotic light field depends on wind speed, wind gustiness, and microphysical properties of bubbles. Incoming field projects and laboratory studies should give a clearer answer on the influence of bubbles on marine light fields. In summary we show that the submerged microbubbles are an efficient source of diffuse radiance and, if present, contribute to rapid transition to the diffuse asymptotic regime.

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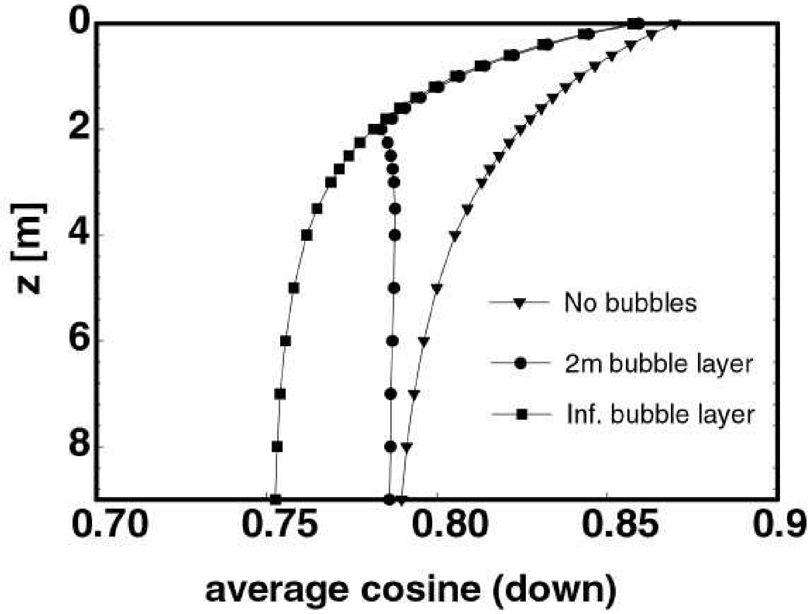

Fig. 2. Average cosine for downwelling radiation $\bar{\mu}_d(z)$ for (1) "infinitely" deep homogeneous ocean composed of CDOM, pure water, and particulates corresponding to chl= $10\mathrm{mgm}^{-3}$ (triangles); (2) "infinitely" deep homogeneous ocean with bubbles (cubes); (3) two-layer system composed of background CDOM, water, and particulates and 2m layer of submerged bubbles close to the surface (circles).

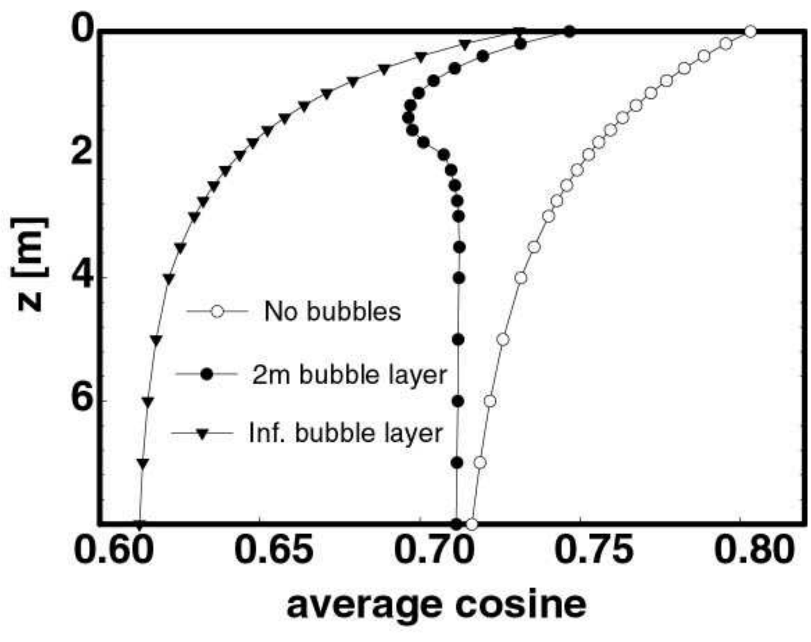

Fig. 3. Same as 2 but for the average cosine $\bar{\mu}(z)$.